IN THE UNITED STATES
PATENT AND TRADEMARK OFFICE

PATENT APPLICATION

Applicant: **Doerr et al.** Case: **Doerr 73-13 (LCNT/125620)**

Serial No.: **10/657,862** Filed: **September 9, 2003**

Examiner: **Kianni C. Kaveh** Group Art Unit: **2883**

Title: **INTEGRATEABLE OPTICAL INTERLEAVER AND DE-INTERLEAVER**

COMMISSIONER OF PATENTS
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S I R:

DECLARATION UNDER 35 C.F.R. § 1.131

We, Christopher Richard Doerr and David S. Levy, hereby declare as follows:

1. We are the inventors of the above-identified patent application.

2. We conceived of the complete invention as claimed in the above-identified patent application on or before March 22, 2003. In addition, due diligence toward reducing the invention to practice was exercised from the conception date of the complete invention as well as the various portions thereof to a subsequent reduction to practice of the invention.

3. To establish the conception date of the invention disclosed in the above-identified application as being on or before March 22, 2003, Applicants submit an invention disclosure form for the above-identified invention that was prepared by the inventors prior to March 22, 2003. Thus, Applicants' conception

date was on or before March 22, 2003. A subsequent constructive reduction to practice of the invention occurred on September 9, 2003, with the filing of the above-identified application.

We further declare that all statements made herein of our own knowledge are true and that all statements made on information and belief are believed to be true; and further, that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issuing therefrom.

12/8/05
Date

CHRISTOPHER RICHARD DOERR

Date

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Date

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12/15/05

Date

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Silica waveguide cross-connect-type wavelength add-drop with integrated interleavers

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Abstract

We employ silica waveguide technology to integrate two interleavers with a wavelength-selective cross-connect and a star coupler with variable optical attenuators, making a low-start-up-cost flexible add-drop node in a highly compact and fabrication-robust manner. To make the interleavers, we demonstrate a novel desensitized 2×2 coupler.

1. Design

To compete effectively with electronic solutions, wavelength-division multiplexed optical add-drop multiplexers (OADMs) need to have a high flexibility yet a low start-up cost. A start-up node is one that can drop only a subset of channels but maintains the total line capacity and is upgradeable to dropping more channels without complete line interruption. To achieve low cost we chose a simple, robust, all-solid-state technology like thermooptic silica waveguides and integrated all the routing elements onto one compact chip.

We designed a wavelength-selective-cross-connect (WSC)-type OADM node for a 16-channel 100-GHz-spacing wavelength-division multiplexed system. To keep the start-up cost low and yet the flexibility high, the system is divided into two 8-channel 200-GHz-spacing sets via interleavers. The start-up node is shown in Fig. 1a. The even-numbered channels can be dropped and added. The dropping is done via a 1×9 WSC (allowing each drop channel to appear at any port), and the adding is done via a 1×8 star coupler (allowing each add channel to be at any wavelength, assuming tunable transmitters) with variable optical attenuators (VOAs) and a coupler. When the user wishes to also drop and add the odd-numbered channels, a second WSC and a second coupler replace the attenuator in the odd-channel path. This can be done without disrupting the even-numbered channels. To make the system low cost, the de-interleaver, the WSC, the interleaver, and the 1×8 star coupler with VOAs are all integrated onto one silica waveguide planar lightwave circuit (PLC). These four components are left unconnected to each other on the PLC, in order to give the user as much flexibility as possible,

e.g., in case the user wishes the start-up node to drop and add the odd-numbered channels. Figure 1b shows how the node can be arranged in an East-West separable fashion using two of the PLCs, in order to preserve SONET 1:1 protection in the event of a PLC failure/replacement.

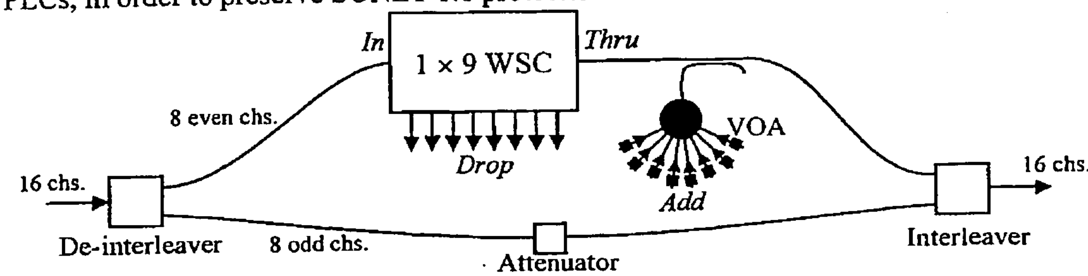

Fig. 1a. Block diagram of proposed low-cost start-up node for a 16-channel system. The de-interleaver, WSC, add 1 × 8 combiner and VOAs, and interleaver were all put on one PLC. To upgrade the node, a second PLC (identical except for a wavelength shift of 100 GHz) is added, replacing the attenuator with a second WSC and add-path coupler.

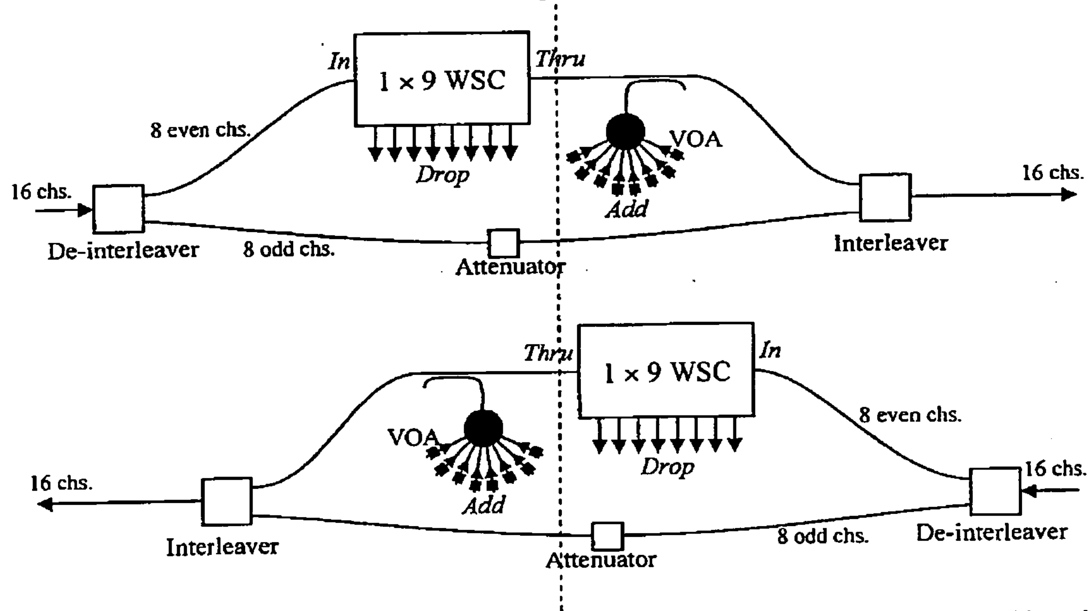

Fig. 1b. Block diagram of start-up node for both directions. To make the system East-West separable, only components from one side of the dotted line are integrated on the same PLC.

The PLC waveguide layout is shown in Fig. 2a. The WSC and add star with VOAs are nearly identical to that of Ref. [1]. The interleavers were squeezed into a small open space, resulting in no change in PLC size, and thus there are still three PLCs per 5" wafer. The interleavers are Fourier-filter type[2], each consisting of a two-stage Mach-Zehnder interferometer (MZI). The interleavers have thermooptic trimmers on the MZI arms to adjust their phases. Because these integrated interleavers need to have a high yield and yet be compact, we used a y-branch coupler for the first coupler and novel three-stage couplers for the second two, as shown in Fig. 2b.

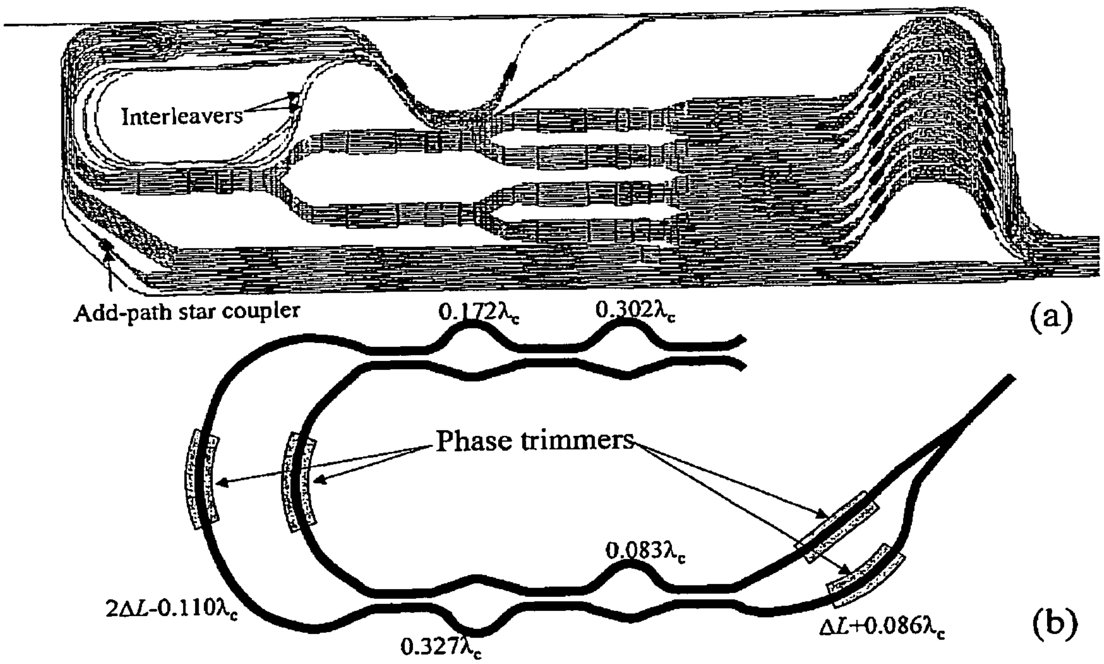

Fig. 2. (a) waveguide layout of the PLC and (b) detailed diagram of an interleaver. The PLC is 9.3 cm × 2.6 cm. The evanescent couplers are nominally 50/50. The numbers tell the local path-length difference, λ_c being the design center wavelength.

It is well known that by combining multiple evanescent couplers one can make a coupler with a coupling ratio that is less sensitive to wavelength, polarization, and fabrication (WPF) variations. Both two-[3] and four-stage[4] "desensitized" arrangements have been proposed. We propose here a three-stage arrangement, consisting of three identical, nominally 50/50 evanescent couplers connected by two differential delays, ϕ_1 and ϕ_2. This three-stage arrangement is ~30% shorter and slightly lower loss than the four-stage one and yet is sufficiently desensitized for our application.

If the inputs to the coupler are u_1 and u_2 (the complex amplitudes of the fields), and the accumulated phase difference between the eigenmodes in each evanescent coupler is $\pi/2 + 2\Delta$, where $\Delta \ll 1$ and represents a error in the coupling ratio, then the outputs v_1 and v_2 are

$$\begin{bmatrix} v_1 \\ v_2 \end{bmatrix} = \frac{1}{2\sqrt{2}} \begin{bmatrix} 1-\Delta & j+j\Delta \\ j+j\Delta & 1-\Delta \end{bmatrix} \begin{bmatrix} e^{j\phi_2} & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1-\Delta & j+j\Delta \\ j+j\Delta & 1-\Delta \end{bmatrix} \begin{bmatrix} e^{j\phi_1} & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1-\Delta & j+j\Delta \\ j+j\Delta & 1-\Delta \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \quad (1)$$

The nominal coupling ratio is

$$R = \frac{1}{8}\left|1 + e^{j\phi_2} - e^{j\phi_1} + e^{j\phi_1 + j\phi_2}\right|^2 \quad (2)$$

The sensitivity of R to Δ is minimized when

$$\left[1+\cos\phi_2-\cos\phi_1+\cos(\phi_1+\phi_2)\right]\left[-1-\cos\phi_2-3\cos\phi_1-\cos(\phi_1+\phi_2)\right]=$$
$$-\left[\sin\phi_2-\sin\phi_1+\sin(\phi_1+\phi_2)\right]\left[-\sin\phi_2-3\sin\phi_1-\sin(\phi_1+\phi_2)\right] \quad (3)$$

We thus have two equations, (2) and (3), for two variables, ϕ_1 and ϕ_2. Some computer-found solutions are listed in Table 1.

Coupling ratio	ϕ_1	ϕ_2
50/50	0°	120°
75/25	116.9°	34.2°
90/10	110.1°	58.4°
100/0	90°	90°

Table 1. Some parameter choices for the proposed 3-stage coupler.

ϕ_1 and ϕ_2 can be interchanged and/or both multiplied by a minus sign without affecting the coupling ratio (e.g., 117°, 34° and -117°, -34° and 34°, 117° and -34°, -117° all give the same ratio). If only one angle is multiplied by a minus sign, then the coupling ratio flips (e.g., 117°, 34° gives a 75/25 ratio, whereas 117°,-34° gives a 25/75 ratio).

As is well known, Fourier-filter interleavers exhibit non-zero chromatic dispersion, which can be canceled by cascading two stages[5,6]. In our case we adjust the MZI arm lengths in one of the interleavers to shift the wavelength response by half of the interleaver free-spectral range[4]. Thus the net chromatic dispersion for the undropped channels is zero.

2. Results

The PLCs were made using 0.80% index-step silica waveguides on a silicon substrate. One was fully packaged with its own drivers on a circuit board. One phase shifter on one MZI arm of each of the stages of each interleaver were accessed via probe needles connected to voltage sources. These two voltages were adjusted so as to wavelength-align the interleaver to the WSC passbands and to optimize the crosstalk. For ~ 5 seconds, each voltage was increased to an extremely high value and then decreased, so as to trim via hyperheating[7]. This process was repeated until both applied voltages became zero, leaving the interleaver permanently adjusted and passive.

The add-star coupler path transmissivities for all 8 inputs are shown in Fig. 3 with the VOAs set at 0- and 10-dB attenuation. The VOAs are operated push-pull[8], and the polarization-dependent loss (PDL) of the entire add path over the 10-dB range is < 1.0 dB. To achieve such uniform, relatively low-loss performance, we used a symmetric star coupler (except for a port shift) with strong mutual coupling and focusing on the phase centers in the arrays[9], along with segmentation[10] and parallel inlet horn walls[11].

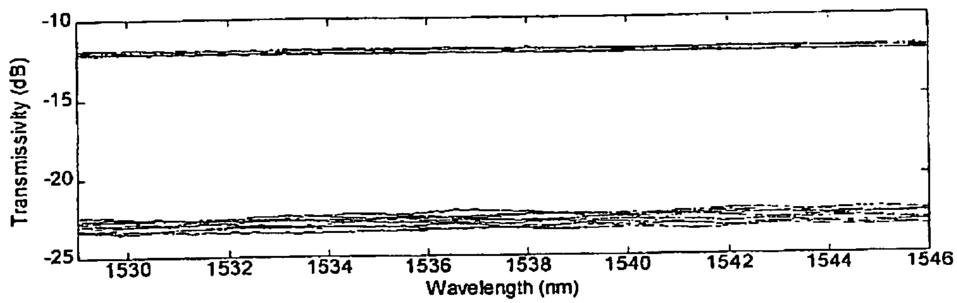

Fig. 3. Measured spectra of the eight add paths with VOAs at 0- and 10-dB attenuation. Fiber-to-fiber, including one connector (likewise for all subsequent plots).

The in-to-thru spectra of the WSC for three different configurations are shown in Fig. 4. The worst-case loss is < 4.75 dB, and the worst-case extinction ratio is > 55 dB. The thru shutters also act as VOAs, and the in-to-thru worst-case PDL at 0-dB and 12-dB attenuation are 0.1 and 0.6 dB, respectively. The in-to-drop spectra of the WSC for sending all 8 channels to each of the 8 drop ports in succession are shown in Fig. 5. The worst-case loss is < 7.5 dB, and the worst-case extinction ratio is > 43 dB. Shown overlaid are the spectra measured at the ports with only double rejection. To be sure that the extinction ratio is adequate for all 9^8 possible states of the WSC without measuring them all, we toggled each of the switches/shutters individually, with and without its neighbors activated (to account for thermal crosstalk) and measured the worst-case extinction ratio of each switch/shutter over all polarizations. We found that the worst-case extinction ratios of all 72 shutters are between 22.6 and 39.2 dB and of all 64 1 × 2 switches, for both up and down states, are between 20.0 and 36.6 dB. Thus the worst possible crosstalk is 42.6 dB.

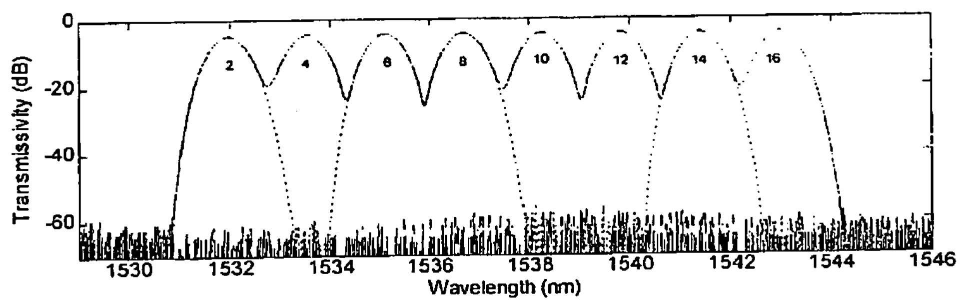

Fig. 4. Measured in-to-thru spectra of WSC for three cases overlaid: no channels dropped, all channels dropped, and only channels 4, 10, and 12 dropped.

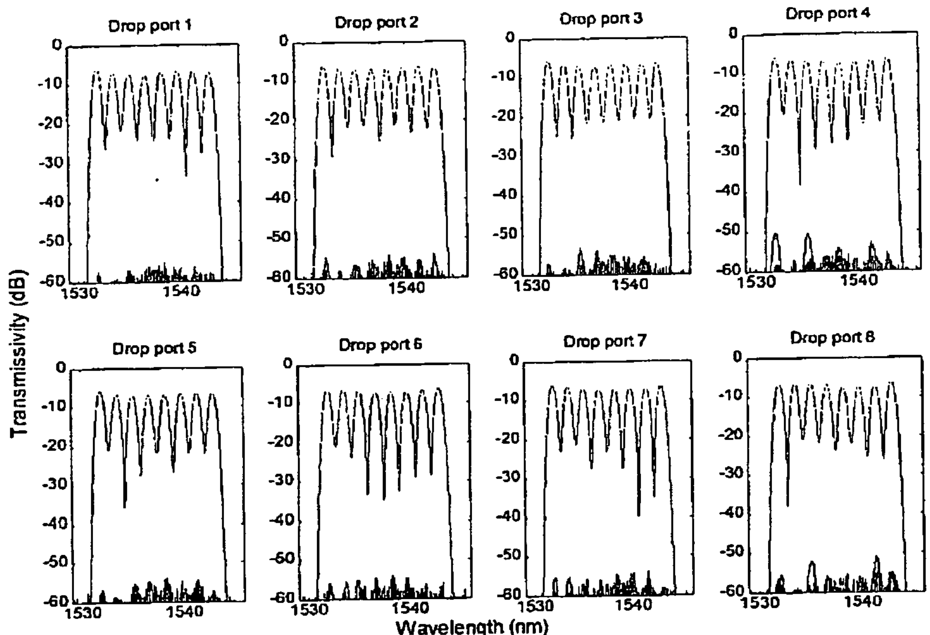

Fig. 5. Measured in-to-drop spectra of WSC for cases of sending all channels to each drop port for each figure. Overlaid are the measured spectra at the ports with only double crosstalk rejection.

The measured spectra of the interleavers are shown in Fig. 6. The loss ranges from 2.25 dB to 3.25 dB. The PDL is 0.1 dB. We then constructed the start-up node of Fig. 1a, leaving out the add path, by connecting together the appropriate fibers on the fiber-ribbon attached to the PLC. We chose the outer interleaver as the de-interleaver, because of its better crosstalk. The measured through-path and drop-path spectra are shown in Figs. 7 and 8, respectively. The worst-case through loss is < 10.8 dB. If the add coupler were added, and if it is a 50/50 fiber coupler, the total through loss for the node would be ~14 dB. The measured chromatic dispersion for the through path is shown in Fig. 9. The magnitude is < 8 ps/nm over the passband.

We thank M. Zirngibl for support and J. Fernandes for assistance.

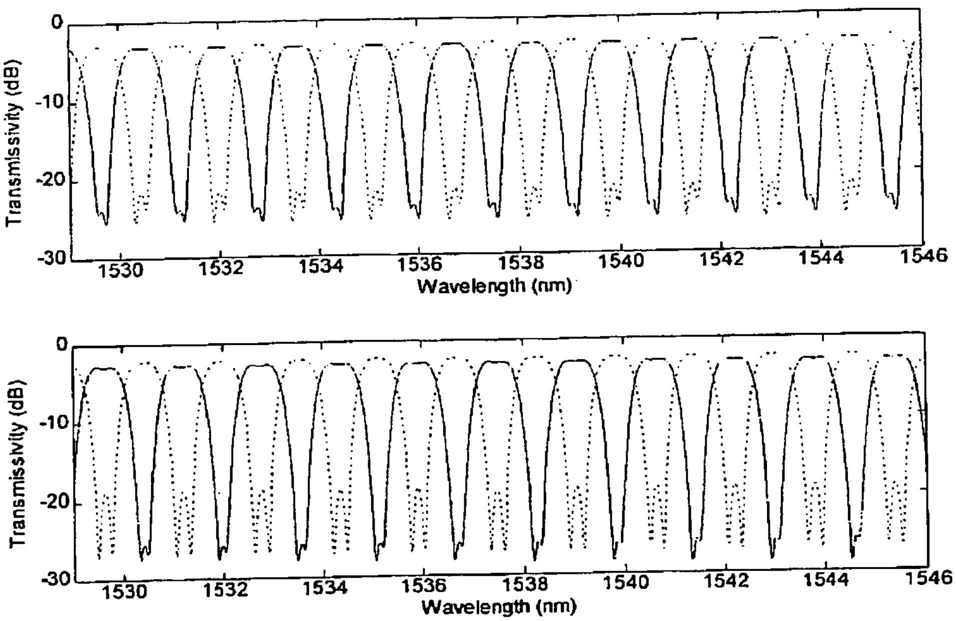

Fig. 6. Measured spectra of interleavers. Upper and lower plots are the outer and inner interleavers, respectively.

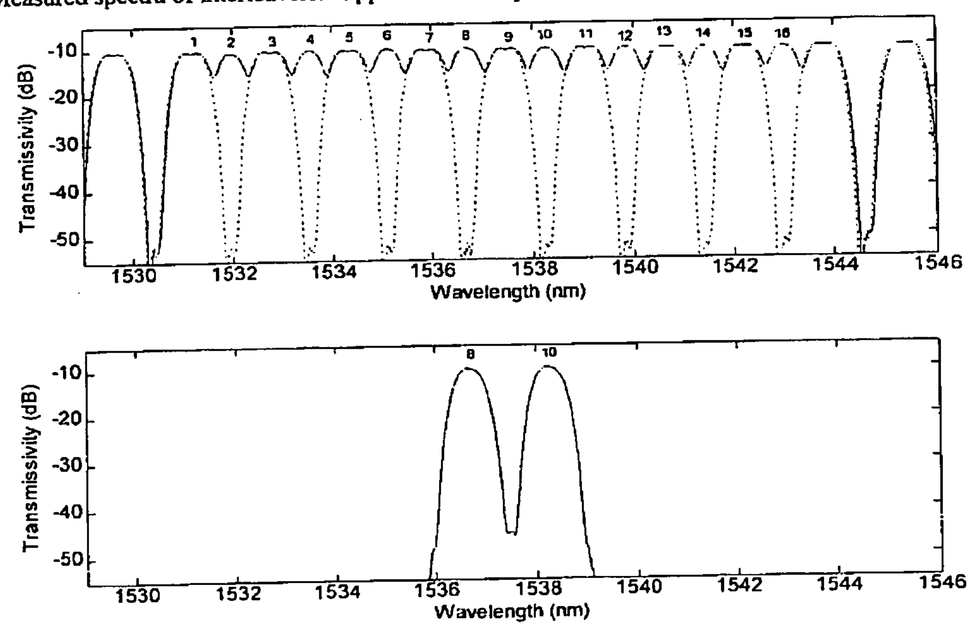

Fig. 7. Measured spectra of the start-up node. Upper plot is from input of de-interleaver to output of interleaver for the cases of no and all channels dropped. Lower plot is from input of de-interleaver to drop port 5 for the case of channels 8 and 10 dropped to drop port 5.

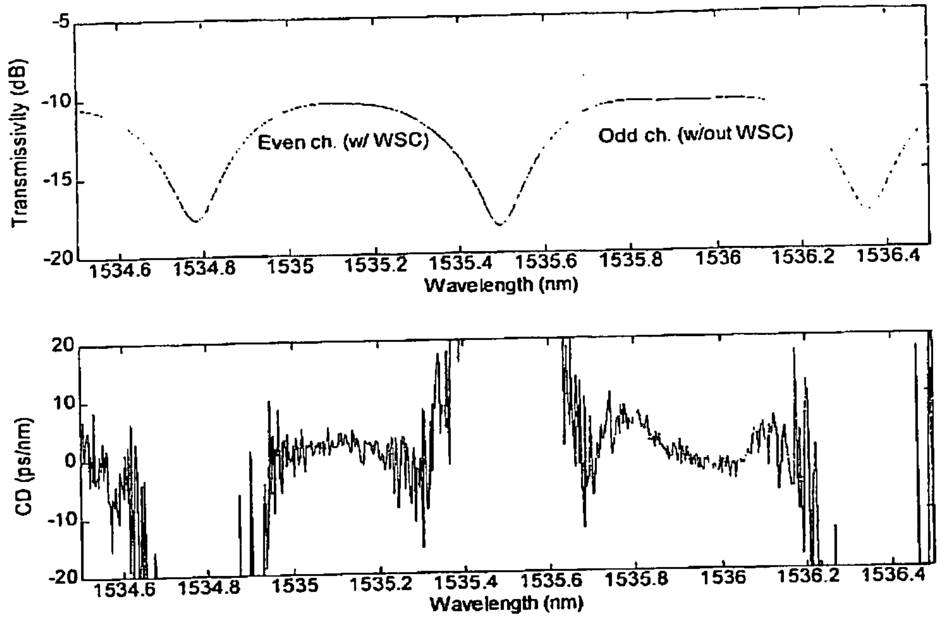

Fig. 8. Measured transmissivity and chromatic dispersion of through path of the start-up node.

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